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Sustainability of Irrigation: An Overview of Salinity Problems and Control Strategies

J. D. Rhoades
US Salinity Laboratory

A. Introduction: Irrigated Agriculture Needs to Be Sustained and Rejuvenated

The primary objective of agriculture is to provide the food and fiber needs of human beings. These needs increase as the population increases; additionally, the demand increases as average income increases. The world population is projected to be 6.3 billion in the year 2000 and 8.5 billion in 2025 (UN, 1990). The average income of much of this population is also increasing. The population increases alone will require an estimated increase in agricultural production of about 40 to 50 percent over the next thirty to forty years (a 20 and 60 percent increase for developed and developing countries, respectively), in order to maintain the present level of food intake. This conclusion is based on recent estimates of the Food and Agriculture Organization of the United Nations (FAO) that the global demand for food, fiber and bio-energy products is growing at an annual overall rate of 2.5 percent and at a rate of 3.7 percent in developing countries (FAO, 1987). According to the UN (UNEP, 1992), the annual rate of increase in agricultural production during the period 1970 to 1990 was about 3% in the developed countries and about 2% in the developing countries. Given these data, it is concluded that many countries of the world must increase their ability to produce food and/or to control population, if they are to meet their future food needs.

According to FAO (FAO, 1989), the potential area of arable land in the world is 3190 Mha, about 46 percent of which is already under cultivation. Worldwide, the area of cultivated land increased by only 4.8 percent over the period 1970-1990 (0.3 % in developed and 9% in developing countries). The per capita arable land decreased from a worldwide average of 0.38 ha in 1970 to 0.28 in 1990, mainly due to the relatively larger increase in population than in new land for agriculture. It has been estimated that, if the arable land is maintained constant at the present worldwide level of 1474 Mha, the per capita arable land will progressively decline to 0.23 ha in 2000 and to 0.15 ha in 2050. It also has been estimated that nearly two-thirds of the increase in crop production needed in the developing countries in the next decades must come from increases in average yields, since only a fifth is expected from increases in arable lands and the balance from increases in cropping intensity (FAO, 1988). About two-thirds of the increase in arable lands is expected to come from the expansion of irrigation. It may be concluded, given the above and additional data given later, that the needed increases in food production in developing countries must come primarily from irrigated land, if the world is to stand a chance of avoiding mass starvation in the future.

Food famines were predicted to occur in many parts of the world beginning in the 1960s. These famines did not occur. Their avoidance was credited to the so-called "Green Revolution". I believe that this avoidance more deservedly should have been credited to the "Blue Revolution", by which I mean the rapid increase in the development of water supplies and irrigation projects that occurred around the world during the period 1950-1980. During this period the rate of growth in irrigation exceeded the rate of population increase (see Table 1 and Figure 1-calculated from data of Ghassemi et al., 1995 and FAO, as assembled by the Worldwatch Institute, 1997, respectively). The expected increase in production from the increase in irrigation and the increased yield that results from irrigation can largely account for the preponderance of the increase in food production that occurred and which met the needs of the expanding population during this period. Of course, the higher yielding varieties of wheat, rice and corn developed during the early part of this period also helped in this regard. But, it seems important to correctly separate the relative contributions of these two factors, not so much in order to correctly credit the exact sources of the past increases in food production but so as to be able to better plan for the future.

Irrigated land presently accounts for about 15 percent of the cultivated land but produces 36 percent of the world's food (FAO, 1988). In the developing countries, almost 60 percent of the production of major cereal grains, rice and wheat, derives from irrigation (Field, 1990). The world's irrigated land is variously estimated to be 220 million hectares (Jensen et al., 1990), 227 million hectares (Ghassemi, et al., 1995) or 244 million hectares (FAO records compiled by Worldwatch Institute, 1997). About three-quarters of the irrigated land is found in the developing countries; by the year 2000 this proportion is projected to be about 90 percent.

It has been estimated that expansion in irrigation overall needs to be 2.25 percent per year in order to meet world food needs by the year 2000 (FAO, 1988). However, the present rate of expansion in irrigation has recently slowed to less than 1 percent per year (CAST, 1988). This rate has been rapidly declining since the 1960s; the percent compounded rates of increase in irrigation were estimated to be 4.1 in 1960, 3.5 in 1970 and 2.3 in 1980 (see Table 2, after Jensen, et al., 1990, and Table 3, after Smedema, 1995). The rate of increase in irrigation fell below the rate of increase in population beginning about 1979 (see Figure 1). The reasons for this slowing in expansion rate of irrigation, or even of a net loss, are many. Among them are the high cost of irrigation development and the fact that much of the suitable land and water supplies readily available for irrigation have been already developed. Lack of available water is the limiting constraint for almost 600 million hectares of potentially suitable arable land (FAO, 1988). Another reason for the current slowed expansion in world irrigation is the fact that the overall performance of many irrigation projects has been less than expected due to inadequate operation and maintenance and to inefficient management (FAO, 1990). It is not unusual to find that less than 60 percent of the water diverted or pumped for irrigation is actually used in crop transpiration. Furthermore, as will be shown in Section B, improper irrigation has resulted in substantial degradation of the presently developed soil resources (which most likely

Table 1. Population and area of irrigated land in world since the year 1800 (data obtained from Ghassemi, et al., 1995 and Worldwatch Institute, 1997).

World Irrigated Area and Population Over Time			
Year	**Population (billions)**	**Irrigated area (Mha)**	**Ha per 1000 people**
1800	1	8	8
1900	1.5	40	26.7
1950	2.5	94	37.6
1961	3.07	139	45.3
1965	3.35	151	45.1
1970	3.71	169	45.5
1975	4.08	190	46.6
1979	4.37	209	47.8
1980	4.45	211	47.4
1985	4.86	226	46.5
1990	5.30	239	45.1
1994	5.63	249	44.2

Table 2. Rate of increase in area of worldwide irrigation agriculture during the period 1960-1984 (data obtained from Jensen, et al., 1990).

Rate of Increase in Irrigation Area Over Time	
Year	**Percent**
1960	4.1
1970	3.5
1980	2.3
1984	1.0

Table 3. Rate of expansion in the world's irrigated area (after Smedema, 1995).

Expansion of World's Irrigated Area Since 1800	
Period	**Mha per year**
1800-1900	0.3
1900-1940/45	1.0
1940/45-1970	5.0
1970-1980	4.0
1980-1990	2.0

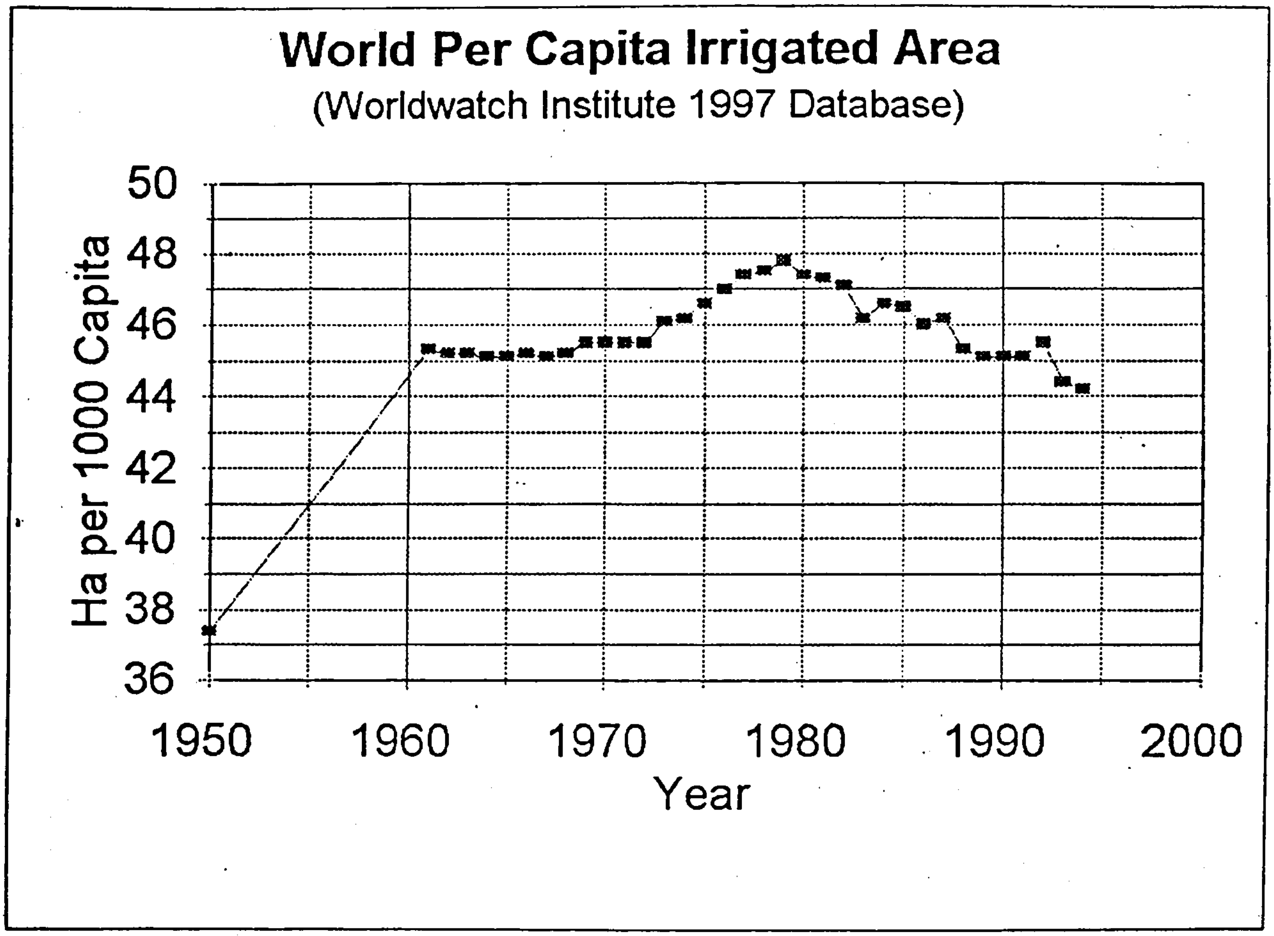

Figure 1. World Irrigated Area per Capita, 1950-1994; data from FAO as summarized in Worldwatch Institute-1997 Database.

have not been adjusted for in the statistics presented above for the area of irrigated land; hence the effective soil resources available for crop production is likely less than the statistics would indicate) and is increasingly causing environmental and ecological concerns about the viability of present projects, as well as discouraging further development. According to David Seckler, Director General of the International Irrigation Management Institute, the losses now are likely exceeding the gains (Seckler, 1996). According to Umali (1993), the salinity affected area is growing at a rate of about 1-2 Mha per year which is of the same order of magnitude as the annual expansion of the world's total irrigated area. The facts given above support the conclusion that there is a great need, on a world-wide basis, to sustain irrigated agriculture. The data presented in Section B will show the additional great need and opportunity that exists to rejuvenate the presently developed but degraded irrigated lands

Given the greatly slowed rate of irrigation development referred to above, the apparent reduced ability to alter this slowing trend and the extensive degradation in presently developed irrigated lands (and in associated water supplies, as will be shown in Section B), the mass famine being predicted to occur in another few decades in many parts of the world should be taken very seriously and should be considered much more likely to occur than the one predicted for the 1960s. Since the crop breeding programs have not been producing much in the way of higher yielding crop varieties in the past couple of decades, the expectations of a truly "green" revolution happening to counter this predicted famine are not very optimistic (Brown, 1997; York, 1994). To illustrate, the worlds rise in land productivity has dramatically slowed in the 1990s to a rate of only 0.5% per year; it increased at a rate of 2.5% per year during the period 1950-1986 (York, 1994). In fact, it has been concluded that most cereal crops may have already attained their physiological limits to further yield increases, especially regarding water use efficiency (Sinclair, 1994). If this is true, the demands on our limited soil and water resources will become even more important to the challenge of meeting our expanding food production requirements.

According to the Panel on Food, Agriculture, Forestry and the Environment of the World Commission (1987), " The next few decades present a greater challenge to the world's food systems than they may ever face again. The efforts needed to increase production in pace with an unprecedented increase in demand, while retaining the essential ecological integrity of food systems, is colossal, both in its magnitude and complexity. Given the obstacles to be overcome, most of them man-made, it can fail more easily than it can succeed."

From the facts and projections cited above it is concluded that: (i) global food needs are increasing markedly while soil and water resources are becoming more limited, (ii) there is a major need to conserve water, to utilize it more efficiently and to protect its quality, and simultaneously to protect soil resources, and (iii) world agriculture must both expand its base of production and produce more with presently developed resources. Because higher yields are obtained with irrigated agriculture and because it is less dependent on the vagaries of weather, it assumes special importance in this regard; it must not only be sustained, it must be rejuvenated. Expansion of irrigated agriculture could also contribute significantly towards achieving and stabilizing our food and fiber needs. However, new water supplies for such expansion are limited. Irrigated agriculture is already the largest consumer of developed water resources. Due to the limited water resources of the world, emphasis should be placed on making more efficient use of the presently developed irrigation-water resources and on the use of waste waters for irrigation. Emphasis should also be placed on sustaining the irrigated land that already is in existence and on increasing crop production on it, especially that which is now degraded..

B. Soil and Water Degradation Resulting from Irrigation/Drainage

In many locations around the world, strains upon the environment are occurring increasingly and concern is mounting about the sustainability of irrigated agriculture due to waterlogging, salinization, erosion, desertification, loss of biological diversity, waterborne diseases, and the adverse effects of potentially toxic agricultural chemicals upon human health and the biota of associated ecosystems (World Commission on Environment and Development, 1987). Presently, 5 to 7 million hectares of arable land (0.3 - 0.5 percent) are being lost every year through soil degradation. The projected loss by the year 2000 is 10 million hectares annually (0.7 percent of the area presently cultivate d). Soil salinization is identified as one of the major causes of chemical soil degradation; waterlogging is identified as one of the major causes of physical soil degradation. Thus, a critical need facing many countries is to halt and to reverse the present extent of environmental degradation resulting from excessive irrigation and drainage, especially those manifested in waterlogging and soil and water salinization, in order to ensure the food needs of the future generations. FAO has concluded that the future expansion of food production will be increasingly dependent upon sound irrigation and soil & water management and upon the concurrent maintenance of the present agricultural resource base and the environment and that these are among the most challenging tasks facing mankind today (FAO, 1988), especially in the Near East Region (FAO, 1995).

The scope and nature of the soil and water degradational problems associated with irrigation will be discussed in some detail in this Section, in order to better define the nature, extent and causes of these problems.

1. Extent and Causes of Soil Degradation

While there is no doubt that large and increasing proportions of the world's irrigated land are deleteriously affected by salinity and water–logging, no one knows for sure the exact extent of their affected areas. It has been variably estimated that the salinized area is as low as 20 and as high as 50 percent of the world's irrigated land (Adams and Hughes, 1990). The results of the Global Assessment of Soil Degradation (GLASOD) reported by Oldeman et al. (1991) estimated that worldwide 76.6 Mha of land have been degraded by human-induced salinization in the last 45 years, but the separation between irrigated and non-irrigated land was not made. Buringh (1977) estimated that the world is losing at least three hectares of arable land every minute to soil salinization (about 1.6 Mha per year), second only to erosion as the leading worldwide cause of soil degradation. Dregne et al.

(1991) estimated that about 43 Mha of irrigated land in the world's dry area are affected by various processes of degradation, mainly waterlogging, salinization and alkalization. They also estimated that the world is losing about 1.5 Mha of irrigated land each year due mainly to salinization. Umali (1993) reported a similar rate of loss by salinization. Ghassemi, et al. (1995) reviewed many of the various sources and estimates on the extent of soil degradation by salinity. They estimated that about 20 percent, or 45.4 Mha out of the total of 227 Mha of irrigated land, are salt affected. They arrived at this number by extrapolating the average percentage reported by others for the five countries with the most irrigated land, ie. India, China, US, Pakistan and the former USSR No continent is free from salt–affected soils; serious salt–related problems occur within the boundaries of at least seventy–five countries (Szabolcs, 1989; Ghassemi et al., 1995). Countries with serious salinity problems include Australia, China, Egypt, India, Iraq, Mexico, Pakistan, Soviet Union, Syria, Turkey, and United States. The 1977 United Nations Conference on Desertification estimated that 22 Mha of the world's irrigated lands are waterlogged (Holdgate et al., 1982). According to the GLASOD report, 10.5 Mha of land became degraded by waterlogging by human activity over the last 45 years. White (1978) concluded that 50 percent of the irrigated soils in the Euphrates Valley in Syria, 30 percent in Egypt and more than 15 percent in Iran are affected by salinity or waterlogging. Based on information derived from the FAO/UNESCO Soil Map of the World, Mashali (1995) estimated that 83.4 Mha of land area (not necessarily arable land) in the Near East Region is salt-affected. He also concluded that countries in the Near East Region most affected by human-induced soil salinization include Egypt, Iran, Iraq, Pakistan, Syria, Turkey, Algeria, Tunisia, Sudan and the Gulf States. Mashali further characterizes and summarizes the salinity problem in the Near East as follows:

> "In Iraq, salinity and waterlogging are problems in more than 50% of the lower Rafadain Plain. In Syria, about 50% of the irrigated land in the Euphrates Valley is seriously affected by salinity and waterlogging. In Egypt, about 33% of irrigated land is affected by varying degrees of salinity and sodicity. In Iran, a combination of salinity, sodicity and waterlogging creates problems in over 15% of the area. In Pakistan, out of a total 15 million Ha of irrigated land, about 11 million ha are affected by salinity, waterlogging or both to varying degrees. Of the 3 million ha recently surveyed in Algeria, 600,000 ha were classified as salt-affected soils, mainly of irrigated land in Oued Chaliff Governorate. Salt-affected soils in Tunisia cover about 1.5 million ha, of which 200,000 ha are irrigated."

A summary of some of the above estimates of the percentages of irrigated land affected by salinization in selected countries and the world is given in Table 3.

The data cited above is extremely qualitative and observational in nature because a practical means to measure the extent and severity of salinized land has been lacking till now. The numbers can not be assumed to be accurate. But for our purposes it doesn't matter, since regardless of the exact numbers, it is obvious that the worldwide area of salinized soil is enormous. Furthermore, it has been concluded by experts of the ICID, World Bank and FAO, who should know, that "the greatest technical cause of declining agricultural productivity on irrigated land, or irrigation failure, is waterlogging and salination of the soil in arid and semiarid regions" (Jensen et al., 1990). Another international group of irrigation and population/food production specialists deliberated such problems at the United Nations Conference on Desertification (UNCOD) held in Nairobi in 1992. Their deliberations led them to make the following recommendation (UNEP, 1992):

> "It is recommended that urgent measures be undertaken to combat desertification by preventing and controlling waterlogging, salinization and sodication by modifying farming techniques to increase productivity in a regular and sustained way, by developing new irrigation and improvement of the soil, social and economic conditions of people dependent on agriculture."

It is evident in the above-mentioned data and reports that waterlogging and salinity are typically combined, or at least not clearly separated, in the assessments. This is because a close relationship exists between the depth of the water table, the salinity of the groundwater, the soil hydraulic properties and the extent of salt accumulation in soils, especially in natural, semi–arid regions. The major saline regions of the world are generally found in semi–arid and arid regions and in relatively low–lying, poorly drained lands. This generally is the result of the mobilization of large quantities of salt present initially in the soils and underlying substrata through the effects of excessive irrigation and leaching and the redistribution and subsequent accumulation of the mobilized salt in localized areas of restricted drainage. Areas of restricted drainage are typically found in lower–lying regions of the landscape where the water table is near the soil surface, and it is in such places that the salts typically accumulate in the topsoil due to evaporation–driven, water-flow processes. Likewise, the occurrence of shallow groundwaters themselves often are similarly related to topographic position. The drainage of waters from the higher–elevation regions of valleys and basins may raise the groundwater level in the lower–lying lands so that it becomes too close (within 2 m) to the soil surface. Permeability of the soils is typically lower in these basin positions because of the higher content of clays generally found in basin soils, which impedes the downward movement of water and results in poor drainage. Many irrigation projects are located in these lower lying alluvial-fan and basin–position areas because of their favorable slopes (more level conditions) for irrigation and closer proximity's to easily accessible water supplies.

While salt–affected soils occur extensively under natural conditions, the salt problems of greatest importance to agriculture arise when previously productive soil becomes salinized as a result of agricultural activities (so–called secondary salinization). As explained above, the extent of salt-affected areas have been modified considerably by the redistribution of water (hence salt) through irrigation and drainage. The development of large–scale irrigation and drainage projects, which involves diversions of rivers, construction of large reservoirs and the irrigation of large landscapes, causes large changes in the natural water and salt balances of entire geohydrologic systems. The impact of such developments can extend well beyond that of the immediate irrigated area; even neighboring nations can be affected. It is not unusual to find that less than 60 percent of the water diverted for irrigation is used in crop transpiration (Jensen et al., 1990). According to Bybordi (1989), the irrigation application efficiency in Iran is seldom above 20 percent. Irrigation water infiltrated into the soil in excess of that used by the agricultural crops passes beyond the root zone. As mentioned above, this drainage water often dissolves salts of geologic origin from the soils and underlying substrata and causes waterlogging in the lower areas where it accumulates. When this occurs, soluble salts present in the soil and substrata are mobilized and transported to the lower areas where they accumulate and over time salinize the soils and groundwaters. Seepage from unlined or inadequately lined delivery canals occurs in many irrigation projects and is often substantial. Law et al. (1972) estimated that 20 percent of the total water diverted for irrigation in the United States is lost by seepage from conveyance and irrigation canals. Biswas (1990) estimated that 57 percent of the total water diverted for irrigation in the world is lost from conveyance and distribution canals. These seepage waters typically percolate through the underlying strata (often dissolving additional salts in the process), flow to lower elevation lands or waters and add to the problems of waterlogging and salt–loading associated with on–farm irrigation inefficiencies there. A classic example of the rise in the water table following irrigation has been documented in Pakistan and is described in Jensen et al. (1990) and Ghassemi et al. (1995), after Greenman et al. (1967). The depth to the water table in the irrigated landscape located there between three major river-tributaries rose from 20 to 30 meters over a period of 80-100 years, ie. from pre-irrigated time (about 1860) to the early 1960s, until it was nearly at the soil surface. In one region, the water table rose nearly linearly from 1929 to 1950, demonstrating that deep percolation and seepage resulting from irrigation were the primary causes. Ahmad (1986) concluded that about 50 percent of the water diverted into irrigation canals eventually goes to the groundwater by seepage and deep percolation. In 1986, Aziz (1986) estimated that about 10 million hectares of cultivable land was waterlogged in Pakistan.

It should be understood that some soil (and water) salinization is inevitable with irrigation (Rhoades, et al., 1974). Typical irrigation waters contain from 0.1 to 4 kg of salts per m^3 and are generally applied at annual rates of 1.0 to 1.5 m. Thus, from 1 to 60 metric tonnes of salt per hectare may be added to irrigated soils annually. The salt contained in the irrigation water is left in the soil as the pure water passes back to the atmosphere through the processes of evaporation and plant transpiration. Therefore, some water in excess of evapotranspiration must be applied with irrigation to achieve leaching and to prevent excess salt accumulation in the rootzone. Thus, some water must drain from the rootzone if irrigation is to be sustained. But, as explained above the amount is excessive and, along with canal seepage, a major general cause of salinization and waterlogging on the large scale.

More exact inventories of soil salinization and waterlogging are needed, as are practical monitoring and assessment procedures to detect trends and identify the root-causes of these problems operating at field- and regional-scales, in order to better deal with these problems. Such a methodology is described later in Section C.

2. Extent and Causes of Water pollution

Irrigated agriculture's' role in salinizing soils has been well recognized for hundreds of years. However, it is of relatively recent recognition that salinization of water resources from agricultural activities is also a major and widespread phenomenon of great concern. Indeed, only in the past decade has it become apparent that trace toxic constituents, such as Se, Mo and As, in agricultural drainage waters may cause pollutional problems that threaten the continuation of irrigation in some projects (Letey et al., 1986; Letey, 1994).

As explained above, water infiltrated into the soil in excess of that used by the agricultural crops passes beyond the rootzone containing most of the applied salts in a reduced volume of higher concentration. This water, together with that percolating downward from canal seepage, often dissolves additional salts (over and above those present in the irrigation water) from the soil and underlying substrata. Such concentrated and additionally mobilized salts, when transported to receiving waters, are generally a source of pollution. Additional potential sources of pollutants from irrigation are the agrochemical (fertilizers and pesticides) applied to the soils which may also be, in part, mobilized (by leaching) and discharged in the drainage water. These salinized and otherwise polluted drainage waters reduce the potential usability of better–quality, receiving–waters when they are allowed to co–mingle with them.

Almost all countries which have soil salinity problems, also suffer from water salinization problems caused by the consumption of the water in crop production and from the discharge of salinized drainage water into them. This is particularly true in rivers whose flow is largely consumed through irrigation and whose drainage is returned either directly or indirectly back into it in successive downstream segments. Some examples of such rivers have been reviewed by Ghassemi et al. (1995). The River Murray in South Eastern Australia and the Colorado River in Southwestern United States are two well documented, prime examples in this regard. Another classic example is the Syr Darya River in the former USSR.. In America, 30 percent of the salt load carried in the Colorado River in its lower sections are estimated to be derived from irrigation-related processes. In Iran, six billion m^3 of brackish water flow annually through its major rivers. Much of the salt load of these rivers come from the saline sediments through which the rivers traverse, but substantial amounts result from irrigation-related drainage processes, especially in the cases of the following rivers: Karun, Dez, Zayandeh-Rud, Zarrineh-Rud and Kor. In Iraq, the Tigris River salinity levels measured in 1982 increased from 292 mg/l in Mosul, to 469 mg/l in Baghdad and to 822 mg/l in Qurna, located about 60 km north-west of Basra. Much of this increase is the result of irrigation, though the exact contribution is not known. Some rivers are not so deleteriously affected by irrigation as those discussed above. For example, the Nile River in Egypt is of excellent quality for irrigation (<350 mg/l) throughout much of its length, even though most of its drainage is returned to it (El-Din, 1989). Apparently, this is because the water is so relatively pure in its source (~25 mg/l) and because there is no large source of geologic-salt in the sediments underlying the irrigated lands south of the northern delta region. However, in the northern delta region, which is subject to sea water intrusion, the pickup of salt by the drainage water is huge (Abu-Zeid, 1989). As the river becomes more fully consumed in the future (Egypt's water resources are already beginning to come under severe stress and the intentional use of drainage water for irrigation is already underway), the salinity of the total water supply will increase and become more like drainage water in its composition (Abu-Zeid and Biswas, 1990; Abu-Zeid and Abdel-Dayem, 1991). In Pakistan, the Indus River and its tributaries are major sources of water for irrigation. Like the Nile River, the Indus River is of excellent quality throughout its length, ranging from about 150 to 420 mg/l. The salinity of the Indus River does not increase excessively with distance downstream in spite of the fact that about 70 percent of its average annual flow is diverted for irrigation. In this case this lack of downstream salinization is because there is little return of drainage waters to the river. Pakistan is also fortunate in that a large unconfined aquifer of high hydraulic conductivity underlies the whole of the Indus Plain in Pakistan. Its capacity is about 50-100 times that of the average annual flow of the Indus River system. This aquifer is recharged by rain, the rivers, and seepage from irrigation systems and irrigated fields (Ahmad and Chaudhry, 1990). The salinity of the groundwater in the aquifer increases from about 1000 mg/l in the upper basin (~6.4 Mha) to greater than 3000 mg/l in the lower basin (~6.5 Mha). About 3.65 Mha of the irrigated area is underlain with groundwater of 1000-3000 mg/l salinity (WAPDA, 1988). In addition to salinity, the groundwater quality is polluted with nitrate from fertilizer sources. It has increased from pre-irrigation time nitrate-levels of less than 3 mg/l to present levels that exceed hundreds of mg/l in some places (Sajjad, et al., 1993). Thus, Pakistan has not only an ample supply of surface water that is suitable for the irrigation of most any crop but also large groundwater supplies that are suitable for selected crops. According to Ahmad and Chaudhry (1988), irrigation deliveries to farms in the canal command areas in 1980-1981 was about 120.55 billion m^3, of which 80.4 billion m^3 was supplied by canal water and 40.1 billion m^3 was derived from groundwater. The high proportional use of groundwater for irrigation in Pakistan serves a number of useful purposes besides just water supply. In particular, it helps lower the watertable under the irrigated land which in turn facilitates leaching and thus the control of soil salinity. Most other countries do not have such good and ample surface and groundwater supplies for irrigation. Such countries must be extra careful in conserving water and in protecting its quality. The protection of their limited supplies from excessively drainage return-flows is especially necessary in this regard.

The above discussion points out that it is the excess diversion of water for irrigation, the concentration of this water through evapotranspiration, deep percolation of the concentrated drainage water, mobilization of the additional "geologic" salts encountered by the drainage water in the substrata and return of such salt-laden waters to surface waters that cause the increase in downstream salinity (pollution) that typify many of the river systems used both for irrigation and drainage in the world. Agricultural drainage is sometimes intentionally returned to common water supplies with the intent to conserve water, to increase water use efficiency or to gain additional water to enable the expansion of irrigation . Also, governmental water-quality agencies often deal with agricultural drainage pollution problems by setting allowable concentrations of total salts and specific solutes in the waters that are to be returned to the water supply system, or in the resultant mix of the waters, and by blending or diluting the drainage waters with a good–quality water so that the concentration of total salt (or of a specific solute) in the blend does not exceed a value (the so–called safe limit) that is deemed allowable in the water supply. This practice is presently being undertaken in a major way in Egypt as part of their program to develop new irrigation lands in the eastern and western deserts (Abu Zeid and Abdel-Dayem, 1991). Presently each year, about 13.5 billion m^3 of Egyptian drainage water flows unused into the Mediterranean Sea and coastal lakes. About 65 percent of this drainage water has a salinity of less than 2000 mg/l. Their plan is to blend much of this drainage water with low salinity canal water in order to obtain a mixture of 500-600 mg/l water that will be used for irrigation in the new lands. I think that such blending may be short sighted and counter productive. Those who advocate such blending programs should consider the potential deleterious effect that they can have upon the usability of the total water supply. The blending process generally reduces the maximum practical benefit that can be derived from the total water supply. The return of saline waters to the water supply, even when sufficient dilution occurs to keep the salinity of the mixture within apparently safe limits, reduces the quantity of the total water supply that can be used in consumptive processes which are limited by salt concentration, such as the growth of salt–sensitive crops (the reasons for this are explained below).

The above shows that the extent and areal sources of water pollution related to salinization from irrigation has not been well quantified; an inventory needs to be undertaken in this regard, especially one that considers the effect that salinity has on the potential usability of the water supplies for consumption. A logic is presented later regarding appropriate concepts for assessing such usability. Additionally, a methodology is introduced for determining the areal, diffuse sources of salt-loading from irrigation.

C. Principles, Strategies and Practices for Controlling Salinity

Others have written about the question: is irrigation sustainable? (Letey, 1994; van Schilfgaarde, 1990). I will not repeat nor critique their evaluations, because I agree with their primary conclusions that sustainability is technically possible. Most of the salinity-related degradational problems associated with irrigated agriculture can be prevented, or greatly minimized, with the proper design and operation of the irrigation and drainage systems, together with the implementation of proper crop and soil management practices provided proper political and social structures are in place which permit such undertakings. The implementation of appropriate irrigation/drainage management practices are key, essential requisites to the conservation of the worlds soil and water resources, to the protection of their quality and to the preservation of the irrigation-based agriculture that is needed to meet the food needs of the expanding world population. Implementing an appropriate means of minimizing leaching and disposing of the saline drainage effluent resulting from irrigation are very important in this regard. Furthermore, based on the data presented in Sections A and B, I believe that we have no alternative but to sustain irrigation and, where its productivity has been degraded, to rejuvenate it, if we are to meet our future food needs on a worldwide basis. Therefore, I believe that a more relevant question than is irrigation sustainable is: what must be done to sustain and rejuvenate irrigation from the ravages of salinization and waterlogging?

The attention given to the problem of soil and water degradation to date has not been sufficient to avoid its continuing onslaught upon our dwindling land and water resources, nor to remediate the degradation that has already happened. Seemingly, the governing bodies around the world have not yet taken the impending salinity-threat to our ability to produce enough food for our expanding population seriously enough to plan and implement the programs that are necessary to solve the present problems of soil and water salinization much less than to prepare for the dismal outlook that emerges from the kind of data reviewed above. I believe that the misconception that the "blue" revolution was "green" and primarily due to the accomplishments of plant breeders and geneticists is partly responsible for this. It also has unduly misdirected research and developmental efforts away from soil and water conservation management to bio-engineering and has caused key decision-makers to place undue reliance upon the latter group to meet the increasing worlds food needs. If the conclusions presented in Sections A and B are correct, our future food production capacity will, most likely, be more dependent upon protecting and enhancing the worlds soil and water resources.

This paper was developed with the hope that the information presented will: 1) enhance the awareness of the importance of irrigation to food production and the seriousness of the salinity and waterlogging problems in this regard, 2) encourage the initiation of studies and programs to deal with the present and emerging soil and water salinization problems and , as well, 3) provide some information that planners and managers may use to effectively develop and implement meaningful, effective programs to bring about real solutions to these problems. Towards this goal, the extent of and the major causes of soil and water salinization and some important effects of irrigation/drainage on soil and water quality and on their usability for crop production were discussed in the preceding section, as was the importance of irrigation agriculture to the worlds food productivity capacity. In the following sections, some important needs and principles & strategies for the control of soil salinity and the protection of water quality from irrigation will be highlighted and recommended. The justification for presenting this technical, management information is the belief I have that many well intentioned, but technically misdirected, salinity control programs have been undertaken in the past. I hope to provide a clear and rational focus that decision makers may use as a basis for the selection of alternative management strategies, approaches and practices, ones that will be more appropriate than many that have been used in the past and that even now are being adopted and implemented around the world, to deal with soil and water salinization problems in food production and environmental protection. I want to emphasize that rejuvenation of degraded irrigated lands needs to be distinguished and stressed in this matter, though much of the management that is needed to control the further decline in the productivity of developed irrigated lands will also assist in the rejuvenation of presently salinized lands.

1. Introduction

As explained above, irrigated agriculture is necessary but, like most all of technology, comes with a down side as well. While irrigation has greatly increased crop productivity, excessive irrigation has wasted water and the excessive drainage resulting from it has polluted surface waters and groundwaters, and has degraded the productivity and altered the ecology of vast areas of land in the world. As also reviewed above, contamination of water supplies by drainage is, in many places, posing health risks and surface and groundwaters in many areas are being contaminated by salts, fertilizers, herbicides and pesticides. Toxic chemicals are rendering some developed water supplies unfit for drinking and even for irrigation, in some cases. These pollutants also degrade the recreational use and esthetic value of surface waters. At the same time, costly restrictions are being placed upon irrigation in some places in the world, in order to reduce or mitigate its pollutional drainage-discharges. Finding a suitable, acceptable place for the discharge of drainage water is increasingly becoming a major problem, especially in the developed countries of the world. Blending saline and fresh waters is often undertaken to reduce the pollutional consequences of drainage disposal, but this action reduces the potential usability of the total water supply. Use of polluted waters for irrigation, as will be shown in this Section, limits crop production potential, as well as posing some potential health hazards to the consumers of the food produced with it.

As also explained in the preceding Section, the majority of the soil degradation (salinity and waterlogging) related to irrigated agriculture occurring throughout the world, and of the associated degradation of water-quality as well, are caused by inefficiencies in the distribution and application of irrigation water, the resulting mobilization and accumulation of excess water and salts in certain localized regions related to geohydrologic conditions and to the return of excessively saline drainage waters to fresh water supplies. It is important to note that these problems have occurred even where low-salinity waters have been used for irrigation. Thus it might be argued that the use of saline waters for irrigation can only increase these problems, since more salt will be added to the soils with such waters and relatively more leaching (hence drainage) is required in this case for salinity control of the rootzone. However, as seemingly paradoxically as this may seem to be, such need not be the case. The reuse of certain saline drainage waters should not, as will be discussed later, result in excessively saline soils nor cause waterlogging with proper management. In fact, the interception of drainage waters percolating below rootzones and their reuse for irrigation should reduce the overall (regional basis) amount of soil degradation associated with excessive deep percolation, salt mobilization, waterlogging and secondary salinization that would otherwise occur in irrigated lands (Rhoades, 1989). It should also reduce the water pollution problems associated with the discharge of drainage water to good–quality water supplies (Rhoades, 1989). For these reasons, an integrated irrigation and drainage management system for facilitating the use of saline drainage waters for irrigation is advocated for purposes of water conservation and for minimizing the soil degradational and water pollution problems associated with drainage. This system will be discussed a little more detail later.

To overcome the soil- and water-salinity problems discussed in Section B, new ways must be developed and implemented in the worlds irrigated lands to reduce excessive water uses in irrigation, to reduce soil salinization and water-logging and to protect the quality of associated water supplies and better ways must be found to implement existing technology appropriate to these needs. Efficiency of irrigation must be increased by the development and adoption of appropriate management strategies, systems and practices and through education and training. Reuse of saline drainage water and shallow groundwater for crop production, should be made an integral component of water conservation, soil conservation and environmental protection programs. Effective salinity control measures must be implemented to sustain irrigated agriculture and to prevent pollution of associated water resources. Such measures must be chosen with recognition of the natural processes operative in large irrigated, geohydrologic systems, as well as those on–farm, and with an understanding of how they affect the long-term quality of soil and water resources, as well as crop production. Some practices can be used to control salinity within the crop rootzone, while other practices can be used to control salinity within larger units of management, such as within irrigation projects, river basins, etc. Additional practices can be used to protect off–site environments and ecological systems – including the associated surface and groundwater resources. "On–farm" practices, which consist of agronomic and engineering operations, must be applied by the individual farmers on a field–by–field basis. "District–wide" or "larger organizational basis" practices, which generally consist primarily of engineering structures for water control (both delivery and discharge) and systems for the collection, reuse, treatment and/or disposal of drainage waters, are usually most appropriately applied by the responsible governmental entities.

There is usually no "single–way" to achieve salinity control in irrigated lands and associated waters. Many different/alternative approaches and practices potentially can be combined into satisfactory control systems; the appropriate combination depends upon the specific economic, climatic, social, as well as edaphic and geohydrologic situations. Thus, no specific recommendations are given here for "the" appropriate set of control practices for different situations or countries. They are too numerous. However, there are some important principles, goals and strategies of salinity management that can be given and that should be understood and considered by planners and decision makers in order to facilitate the sustainability and rejuvenation of irrigation. The proper management of salinity and drainage requires an understanding of how salts affect plants and soils, of how geohydrologic processes affect waterlogging and salt accumulation, and also of how cropping and irrigation activities affect soil and water salinity. These principles, goals, strategies and practices will be briefly presented and discussed in the remainder of this paper. References will be given where more detailed information may be obtained. The intent is to provide policy-makers and managers with enough of an understanding in these matters to help guide them to develop and implement the more appropriate irrigation-, drainage- and salinity control- strategies, activities and programs that are needed, in order to better deal with the emerging problems that they will be increasingly faced with in the future. This material is discussed more fully elsewhere (Rhoades, et al., 1992; Rhoades, 1993a). Additionally, some research needs will be identified where present knowledge and methodology is inadequate.

2. Management Goals for Enhanced Crop Production and Soil Protection

Grow Suitably Tolerant Crops

Because different crops and even different cultivars of the same crop vary considerably in their tolerance to salinity, crops should be selected that will produce satisfactorily for the particular existing conditions of salinity and those expected to occur in the rootzone during the growing season. For degraded lands, cropping rotations need to be selected to facilitate rejuvenation. The most comprehensive list of salinity tolerance values of common cultivated crops presently available for use in this regard are those summarized by Maas [1990]. Plant density should also be increased to compensate for smaller plant size that exists under saline conditions. This increases the interception of the incoming energy of the sun, and hence crop yield, relative to normal densities. It is especially important to consider the crop's salt tolerance during seedling development. This is often the most sensitive growth stage (Shannon, [1982]), and optimum yields are impossible without the satisfactory establishment of crop stand. Salt present in the seedbed reduces the rate of germination and thus increases the time to emergence. The stand may then suffer because the seedling is unable to emerge through the soil crusts which result from surface drying, as well as because of the increased opportunity-time for disease problems to develop due to the delay in emergence. When a crust is likely to develop, sowing rate should be increased to facilitate seedling emergence and stand establishment. Other techniques should be used to combat crusts, including the use of various forms of mulching and, in the case of sodic soils, the application of certain tilth-improving amendments, such as gypsum. Some of these techniques are discussed more in the next section. More knowledge of the differences in plant salt-tolerance during the various growth stages need to be established so that the "cyclic" strategy of irrigating with saline waters, which is described later, can be better optimized. Crop-plants of increased tolerance to salinity and associated stresses should be sought and developed through genetics and bio-engineering and halophytes need to be sought and adapted to cropping and the production of useful biomass utilizing saline waters and lands (Shannon, et al., 1993). More attention needs to be directed to developing crop rotations that promote the lowering of water tables, leaching and soil aggregation to help rejuvenate salinized and water-logged soils, while cropping continues. Computer programs need to be developed to adjust salinity analyses made on extracts of gypsiferous soil samples for the additional salts brought into solution during the extraction process, which cause the determined salinities to appear to be erroneously high-since such errors often cause misinterpretations and inappropriate management decisions.

Prevent Excessive Salinity Accumulation in the Seedbed

Excessive salt accumulation can be especially damaging to germination and seedling establishment when raised beds or ridges are used and "wet-up" by furrow irrigation, even when the average salt levels in the soil and in the irrigation water are moderately low. Since salts move with the water, the salt accumulates progressively towards the surface and center of the raised bed or ridge and is most damaging when a single row of seeds is planted in the central position. This is so because salts tend to accumulate under furrow irrigation in those regions of the seedbed where the water flows converge and evaporate; this problem is magnified when saline waters are used for irrigation (Bernstein and Fireman, 1957). Information from this early, classic study show that seedbed and furrow shape can be designed to minimize this problem. Seed placement and surface irrigation strategies (e.g., alternative furrow, depth of water in furrows, etc.) that can be used to optimize plant establishment under saline conditions are described by Kruse et al. (1990). Thus, seedbed shape, seed location and irrigation procedures should be managed to prevent the excessive, localized accumulation of salts in the region of the soil where the young plants roots are developing. Saline, "bed–peaks" can be de-topped to prevent exposure to emerging shoots. With double-row beds, under moderately saline conditions, most of the salt is carried into the center of the bed, leaving the shoulders relatively free of salt and more suitable for seedling establishment. Sloping beds are best suited for soils irrigated with saline waters because the seedling can be established "downslope" below the zone of salt accumulation. The salt is moved away from around the seedling instead of accumulating near it. Planting in furrows or basins is satisfactory from the stand-point of salinity control but can be unfavorable for the emergence of many row crops because of crusting or poor aeration. Pre-emergence irrigation by sprinklers or drip lines placed close to the seed may be used to keep the soluble salt concentration low in the seedbed during germination and seedling establishment. Special temporary furrows may also be used in place of drip lines during the seedling establishment period. After the seedlings are established, the special furrows may be abandoned and new furrows made between the rows; likewise sprinkling may be substituted for furrow irrigation during this critical period. Sprinkler irrigation can be effective in leaching excessive salinity from the top–soil and in producing a favorable low–salinity environment in the upper soil layer which is necessary for the establishment of salt–sensitive seedlings (Bernstein and Francois, 1973). However, other problems (such as foliar injury) are can result from the sprinkling with saline water. Under drip irrigation, the salt content is usually lowest in the soil immediately below and adjacent to the emitters and highest in the periphery of the wetted zone. Removal of salt that has accumulated in this wetting zone "front" must be addressed in the long–term. The management requirements of drip-irrigated crops for such long-term salinity control needs more research and development.

Sodic soils are prone, especially when irrigated with low-salinity waters or when subjected to rainfall, to undergo clay dispersion, disaggregation and slaking and, upon drying and consolidation, to surface crusting (Rhoades and Loveday, [1990]). Frequently the surface soil "sets-up" into a massive layer, or the aggregates fuse together to form a tilth that is too coarse and cloddy for a suitable seedbed. Application of various chemical amendments, such as gypsum and various soil conditioners, should be used to alleviate such conditions, thus enabling better seedling emergence, improved water entry and water storage, increased leaching of soluble salts, reduced tillage costs and greater flexibility of "bedding" operations. Practices which maintain high organic matter levels in the soil, e.g., green manuring and incorporation of crop residues, also help in the maintenance of good tilth. Where structural conditions are likely to hinder seedling emergence and crop establishment, more frequent light irrigations may be applied to soften crusts. More research is needed to quantify the amendment requirements for different conditions of soils, irrigation waters, rainfall and crop management.

Barren or poor areas, in otherwise productive fields, are often high or low spots that receive insufficient or excessive water for good plant growth. Where irrigation is by flood or furrow methods, careful land grading, such as that obtained using laser-controlled earth-moving equipment, is required to achieve uniform water application and consequently better salinity control. Where perennial crops are planned, planting should be delayed after land grading for 1 or 2 years during which time annual crops are grown and the fill-areas allowed to settle prior to re-grading for the permanent planting.

Deliver Water to Fields in Correct Amounts and Timing

Salinity control of irrigated lands generally requires good irrigation management. The prime requirements of irrigation management for salinity control are timely uniform irrigations, adequate leaching, adequate drainage and water table depth control. Various contributing and interacting factors are involved in fulfilling these requirements. These include the delivery system and the method and manner of irrigation. The key to effective, efficient irrigation (and hence salinity control) is to uniformly provide the plants with the proper amount of water at the proper time, without excess. Thus, careful control of timing, of application uniformity and of amount of water applied are prerequisites to high water use efficiency and to high crop yield, especially when irrigating with saline waters. This calls, optimally, for water delivery to the field on demand which, in turn, requires close coordination between the irrigator and the organization that distributes the water; it calls for measurement of water flow (rates and volumes), feedback devices that measure the water and salt content of the soil, ways to predict or measure the rate of water use by the crop and ways to detect or predict the onset of plant stress, and it also calls for the accurate control of volume delivered to each field and its uniform areal distribution within it.

For efficient control of a supply system, the water volume passing critical points, including the outlets to individual fields, needs to be controlled and metered. This demands the installation of effective flow controlling and measuring devices, without which seepage losses are difficult to identify and an over-application of water to fields is likely to occur. Additionally, many delivery systems encourage, if not cause, over-irrigation because the water is supplied for fixed periods, or in fixed amounts, irrespective of seasonal variations in on-farm needs. Such systems also preclude the use of some types of irrigation that are more capable of higher efficiency; such as sprinkler and drip. The optimum drip-irrigation scheme provides water nearly continuously, but very slowly, to keep the soil water content in the rootzone within narrow limits, although carefully programmed periods of stress may be desirable and provided in order to obtain maximum economic yield with some crops; cultural practices also may demand periods of "dry" soil. Thus, for such systems, water delivery needs to be on-demand, which requires appropriate delivery facilities.

Excessive loss of irrigation water from canals constructed in permeable soil contributes considerably to high water tables and the creation of saline soils in many irrigation projects. Such seepage losses should be reduced by lining the canals with impermeable materials or by compacting the soil in the wetted perimeter to achieve low permeability.

The maintenance of the drainage system is also important in this regard and the tile lines or open ditches of the fields and project should be kept clean and on-grade. Over-irrigation also contributes to shallow water table and salinity problems, as well as increasing the amount of water that the drainage system must accommodate. Therefore, a proper relation between irrigation management and drainage must be maintained in order to prevent irrigated lands from becoming salt affected and waterlogged. The amount of water applied should be sufficient to supply the crop and satisfy the leaching requirement but not enough to overload the drainage system. It is important to recognize that inefficient irrigation is the major cause of salinity and shallow water tables in most irrigation projects of the world and that the need for drainage can usually be reduced through improvements in irrigation management. Ways to improve irrigation efficiency should usually be sought <u>first</u> before the drainage capacity is increased.

The primary sources of return flow from an irrigation project are bypass water, canal seepage, deep percolation, and surface (tailwater) runoff. Bypass water is often required to maintain hydraulic head and adequate flow through a gravity–controlled canal system. It is usually returned directly to the river, and few pollutants, if any, are picked up in this route. Evaporation losses from canals commonly amount to only a small percentage of the diverted water. But seepage from unlined canals is often substantial. It may contribute to high water tables, increase groundwater salinity and phreatophyte growth, and generally increases the amount and salinity of the required drainage from irrigated areas. If the water passes through salt–laden substrata or displaces saline groundwater, the salt pickup from this source can be substantial. Canal lining can reduce such water-logging and salt loading. Closed conduit conveyance systems can minimize both seepage and evaporation losses and the use of water by phreatophytes. The closed conduit system also provides the potential to increase project irrigation efficiency and to thus lower salt loading (van Schilfgaarde and Rawlins, 1980). Thus, canals should be lined and closed conduit delivery and drainage systems should be provided, wherever possible, to facilitate salinity control and water conservation.

Irrigate Efficiently with Minimized Leaching and Provide Drainage

As mentioned earlier, the concentrations of soluble salts increase in soils in proportion to the amount and salinity of the irrigation water and as the soil water, but not salt, is removed by evaporation and transpiration. Additionally, evapotranspiration (ET) can cause the upward flow of water (and, hence, salt) from a shallow groundwater into the rootzone, thus also increasing soil salinity. It is by this latter process, that most soils with shallow, saline water tables become salinized. In either case, soluble salts will eventually accumulate in irrigated soils to the point that crop yields will suffer unless steps are taken to prevent it.

To prevent the excessive accumulation of salt in the rootzone from irrigation, extra water (or rainfall) must, over the long term, be applied in excess of that needed for ET and this excess must pass through the rootzone in a minimum net amount. This amount, in fractional terms, is referred to as the "leaching requirement" (L_r, the fraction of infiltrated water that must pass through the rootzone to keep salinity within acceptable levels; US Salinity Laboratory Staff, 1954). In fields irrigated to steady–state conditions with conventional irrigation management, the salt concentration of the soil water is essentially uniform near the soil surface regardless of the leaching fraction (L, the fraction of infiltrated water that actually passes through the rootzone) but increases with depth as L decreases. Likewise, average rootzone salinity increases as L decreases; crop yield is decreased when tolerable levels of average salinity are exceeded. Methods to calculate the leaching requirement and to predict crop yield losses due to salinity effects, under steady-state and uniform field conditions, are described elsewhere (Hoffman, et al., 1990; Rhoades, et al., 1992). Once the soil solution has reached the maximum salinity level compatible with the cropping system, at least as much salt as is brought in with additional irrigations must be removed from the rootzone; a process called "maintaining salt balance." The extent to which leaching and drainage can be minimized is limited by the salt tolerances of the crops being grown, the irrigation system distribution uniformities and the variability in soil infiltration rates. In most irrigation projects, the currently used leaching fractions (and resulting drainage volumes) can be reduced appreciably without harming crops or soils, especially with improvements in irrigation management (van Schilfgaarde et al., 1974). They <u>should be minimized</u> because the prevalent excesses in leaching are a major, fundamental cause of both soil and water salinization, for the reasons explained previously.

To prevent waterlogging and secondary salinization, drainage must remove the precipitation and irrigation water infiltrated into the soil that is in excess of crop demand and any other excessive water (surface or subsurface) that flows into the irrigated soils; it must provide an outlet for the removal of salts that accumulate in the rootzone in order to avoid excessive soil salinization, and it must keep the water table sufficiently deep to permit adequate root development, to prevent the net flow of salt–laden groundwater up into the rootzone by capillary forces and to permit the movement and operations of farm implements in the fields without excessive compaction. Artificial drainage systems should be provided in the absence of adequate natural drainage. The water table depth required to prevent a net upward flow of water and salt into the rootzone is dependent on irrigation management and is not single–valued as is commonly assumed (van Schilfgaarde, 1976). Methods to calculate drainage requirements are given elsewhere (Rhoades, 1974; Kruse et al., 1990; Hoffman et al., 1990).

The time–averaged level of rootzone salinity is affected by the degree to which the soil water is depleted between irrigations, as well as by the leaching fraction. As the time between irrigations is increased, soil water content decreases as the soil dries, and the matric and osmotic potentials of the soil water decrease as salts concentrate in the reduced volume of water. Water uptake and crop yield are closely related to the time- and depth-averaged total soil water potential, i.e., matric plus osmotic. Following irrigation, plant roots preferentially absorb water from rootzone depths with high water potential. As water is removed from a soil with nonuniform salinity distribution, the total water potential of the water being absorbed by the plant tends to approach uniformity in all depths of the rootzone. Normally this means that most of the water uptake is initially from the upper, less saline soil depths until sufficient water is removed to increase the total water stress to a level equal to that in the lower depths. After that, water is removed proportionately more from the deeper, more saline soil depths and the effect of salinity, per se, on crop growth is magnified. This implies that: (i) forms of irrigation that minimize matric stress, such as drip irrigation, should be used to minimize the harmful effects of irrigating with saline water, and (ii) leaching fractions should be increased, as needed, to minimize the buildup (hence harmful effects) of excessive levels of salinity in the deeper regions of the rootzone (Rhoades and Merrill, 1976).

The distribution within and the degree to which a soil profile becomes salinized also are functions of the manner of water application, as well as the leaching fraction. More salt is generally removed per unit of leachate with sprinkler irrigation than with flood irrigation. Thus, the salinity of water applied by sprinkler irrigation can be somewhat higher, all else being equal, than that applied by flood or furrow irrigation with a comparable degree of cropping success, provided foliar burn is avoided. The high salt–removal efficiency of sprinkler irrigation may be explained as follows. Solute transport is governed by the combined processes of convection (movement of solutes with the bulk solution) and diffusion (independent movement of solutes as driven by a concentration gradient); convection is usually the predominant process in flood–irrigated soils. Differential velocities of water flow can occur within the soil matrix because the pore size distribution is typically nonuniform. This phenomenon is called dispersion. It can be appreciable when flow velocity is high and pore size distribution is large; diffusion often limits salt removal under such conditions. Soils with large cracks and well–developed structure are especially variable in their water and solute transport properties because the large "pores" are preferred pathways for water flow, as are earthworm channels, old root holes, interpedal voids, etc.; most of the flow in flooded soils occurs via these "pores". Much of the water and salt in the small and intra–aggregate pores is "bypassed" in flood irrigated soils. Flow velocity and water content are typically lower in soils irrigated with sprinklers; hence, bypass is reduced and efficiency of salt leaching is increased with sprinkler irrigation. Other soil–related processes also affect salt concentration and transport during the irrigation and leaching of soils. In most arid land soils, the clay particles are dominated by negative charges, which can retard cation transport through adsorption and/or exchange processes. Simultaneously, anions are largely excluded from that part of the pore solution adjacent to the negatively charged clay surface; this accelerates their relative transport. The borate anion also undergoes adsorption reactions that retard its movement. For a more quantitative description of effects of convection and dispersion, as well as other soil factors, on solute transport in soils see the reviews of Wagenet (1984) and Jury (1984).

Susceptible crops should not be sprinkler-irrigated with saline water, since their foliage absorbs salts upon wetting. Salts can accumulate in leaves by foliar absorption of such crops until lethal concentrations have been reached. Crop sensitivity to saline sprinkling water is related more to the rate of foliar salt accumulation than to crop tolerance to soil salinity, per se (Maas, 1990). Hence, applications should be made during the night and in a manner to achieve frequent wetting ("washing") of the leaves in order to minimize foliar absorption of salts when irrigating with saline waters by sprinkler methods.